Tire Wear Emissions for Asphalt Rubber and Portland Cement Concrete Pavement Surfaces

Arizona Department of Transportation
Contract KR-04-0720-TRN

Draft Working Paper 2
Progress Report

January 2005

Submitted by

Jonathan O. Allen, Ph.D., P.E.
Olga Alexandrova, Ph.D.
Danial Gonzales

Department of Chemical & Materials Engineering

Kamil E. Kaloush, Ph.D., P.E.
Maria Carolina Rodezno

Department of Civil & Environmental Engineering

Ira A. Fulton School of Engineering
Arizona State University
Tempe, AZ 85287-5306

ARIZONA STATE UNIVERSITY

Table of Contents

1 Introduction

Since 1990, it has been the policy of the State of Arizona that the recycling and reuse of waste tires are the highest priority. The Arizona Department of Transportation (ADOT) has long supported the use of recycled waste tire rubber in asphalt rubber hot mix. AR mixtures have been shown to perform successfully and have several added benefits such as the reduction of highway noise, providing better surface drainage characteristics to enhance visibility and skid on wet pavement surfaces. Furthermore, some aspects of life cycle costs have also been conducted and demonstrated the potential impacts on maintenance and rehabilitation savings to ADOT. Joint ASU/ADOT research activities related to Asphalt Rubber (AR) mixtures started in July 2001 and are continuing. In this work we test the hypothesis that AR-ACFC road surface layer results in significantly less tire wear than PCC road surface layer.

Tire wear contributes to atmospheric particulate matter (PM) which is regulated by the United States Environmental Protection Agency (US EPA) because PM has been shown to affect human health. PM is classified by the size of the particles; PM10 and PM2.5 include particles with diameters smaller than 10 and 2.5 μm, respectively. PM2.5 has been shown to contribute to morbidity and mortality (Dockery et al., 1993; Pope et al., 1995; Katsouyanni et al., 1997; Krewski et al., 2000). This epidemiological research has found consistent and coherent associations between outdoor air quality and health outcomes including respiratory symptoms, reduced lung function, chronic bronchitis, and mortality (Bates, 1992). The PM10 fraction includes particles that are respirable, and so of concern for human exposure.

Vehicle emissions are a significant source of both PM2.5 and PM10. Vehicle fleet emissions per mile traveled have been reduced significantly in the last 30 years as a result of improved engine operation and tailpipe controls; this downward trend is expected to continue into the future and is an important means to reduce PM. The main focus of these reductions has been on tailpipe emissions; however, "zero emission" vehicles will continue to generate PM from tire wear, road wear, brake wear, and re-suspended road dust. These non-tailpipe emissions will become a relatively more important component of PM emissions but are difficult to characterize. In this proposal work, we apply our existing aerosol measurement expertise (Allen et al., 1996; Allen et al., 2001) to evaluate tire wear emissions from the vehicle fleet using the Deck Park highway tunnel in Phoenix, AZ.

The amount of rubber loss was estimated to average approximately 90 mg/km (Dannis, 1974) which corresponds to 1.3 million metric tons per year for the entire US (Reddy and Quinn, 1997). Tire wear particles are generated during rolling shear of the tire tread against the road surface. Average tire tread wear rate for single passenger tire is between 6 and 900 mg/km, depending on the road surface type (e.g., asphalt vs. concrete), driving conditions (acceleration, abrupt deceleration, speeding, etc) and tire conditions (tire pressure, vehicle load, retread vs. new, etc.). Tire wear emissions (TIRE) are estimated in the EPA MOBILE 6.1 model as

$$\text{TIRE} = 0.002 * \text{PSTIRE} * \text{WHEELS}$$

where TIRE has units g/mi, PSTIRE is the fraction of particles smaller than a cutoff size, and WHEELS is the number of wheels on a vehicle (EPA, 2003). For PM10, PSTIRE is 1.0; for PM0.1, PSTIRE is 0.01. Using this formula, a passenger vehicle is estimated to emit 13 mg/km of PM10 and 0.13 mg/km PM0.1. The MOBILE 6.1 emission estimates are used for air quality modeling, however these factors have not been verified experimentally for existing or new pavement surfaces.

We hypothesize that AR-ACFC road surface layer results in significantly less tire wear than PCC road surface layer. Reduced tire wear would result in lower vehicle operating costs and lower particulate matter (PM) emissions from vehicle traffic. In the present research, we measure the rate tire-wear marker compounds in PM emissions at the Deck Park Tunnel Highway on Interstate 10. The Deck Park Tunnel highway surface was PCC until June **, 2004, when it was resurfaced with an AR-ACFC. This research takes advantage of a rare opportunity to sample tire wear emissions at the tunnel before and after the AR-ACFC overlay.

Measured tire wear emission rates developed here may then be used by ADOT as inputs to federally-mandated air quality models for the Phoenix airshed. If, as hypothesized, resurfacing with the AR-ACFC reduces tire wear emissions, this additional benefit of AR may be incorporated in ADOT air quality planning.

2 Objectives

The objectives of this study are:

1. Measure the PM emissions from the on-road vehicle traffic during typical highway driving conditions for two different roadway surfaces: AR-ACFC and PCC.
2. Analyze PM emissions to determine emission factors for tire wear emissions for the two different road surface types. Evaluate the hypothesis that AR-ACFC road surface results in significantly less tire wear emissions than a PCC surface.
3. Collect and analyze representative tire tread samples for tires wear marker compounds including 24MoBT (2-(4-morpholinyl) benzothiazole) and NCBA (N-cyclohexyl-2-benzothiazolamine). Test extraction and separation protocols to determine the amount of 24MoBT and NCBA in tire treads.
4. Relate tire wear emissions to the roughness and frictional characteristics of the two pavement types.
5.

3 Methods

3.1 Tunnel Sampling

Drs. Allen and Kaloush conducted a site visit to the tunnel in April 2004 guided by Mr. George Way and Edward Walsh of ADOT. The experimental design is based on that site visit and the results of experiments at the Deck Park tunnel in January and July 1995 (Gertler et al., 1997).

Gertler and coworkers determined emissions of gas-phase pollutants from the Phoenix vehicle fleet based on measurements of pollutant concentrations the tunnel inlet and outlet. They found that pollutants in the tunnel were poorly mixed with concentrations of pollutants away from the HOV lane was ~1.5 higher than that near the HOV lane. Poor mixing was attributed to the Deck Park tunnel width, 217 m^2 cross section at its narrowest point. Reliable determination of emission factors from tunnel measurements requires uniform concentrations at the exhaust sampling point.

In this experiment, the existing forced ventilation system was used to mix the vehicle emissions in the tunnel. During the experiments exhaust fans in the second half of the tunnel were run in high-flow exhaust mode. Sampling instruments were positioned at the tunnel entrance and at the tunnel exhaust chimney (see Figure 1).

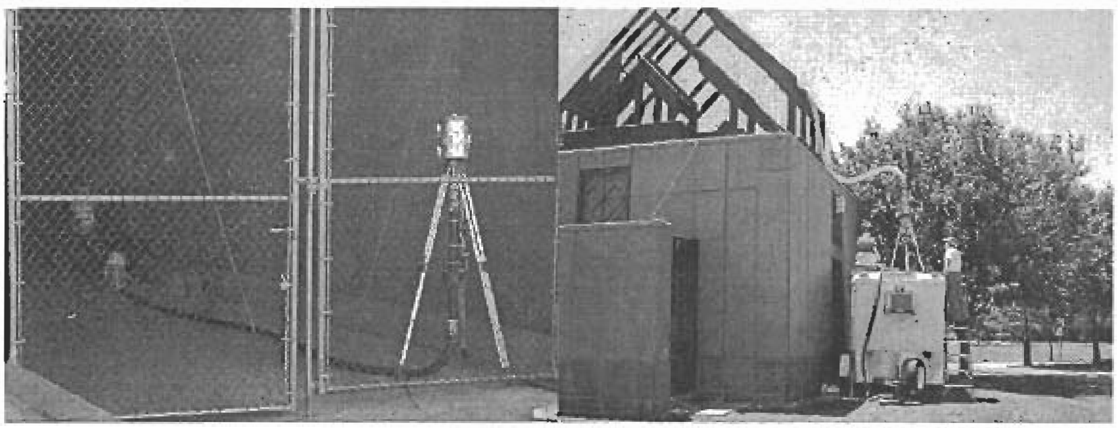


Figure 1: Photos of sampling sites from the May 2004 experiment. Aerosol measurements were made next to entrance of westbound tunnel (left photo) and from the exhaust chimney for the western half of the westbound tunnel (right photo).

Tunnel experiments have been performed on 27-28 May 2004 before the highway was resurfaced and will be performed again in May 2005 (see Table 1). Vehicle emissions were sampled during rush hour (07:00-09:00) and midday (10:00-14:00) in order to measure emissions from the mainly light-duty vehicle fleet during rush hour and the mixed light- and heavy-duty fleet later in the day. In normal tunnel operation, the exhaust fans are turned off at these times.

Table 1. Deck Park Tunnel Experiments

No.	Date	Start	End
PCC road surface			
1	Thu 27 May 2004	10:00	14:00
2	Fri 28 May 2004	07:05	09:05
3	Fri 28 May 2004	10:00	14:00
AR-ACFC road surface (proposed)			
4	Thu 26 May 2005	07:00	09:00
5	Thu 26 May 2005	10:00	14:00
6	Fri 27 May 2005	07:00	09:00
7	Fri 27 May 2005	10:00	14:00

Particulate pollutant concentrations in the tunnel bores were measured using two high volume cascade impactors, ChemVol 2400 (Rupprecht & Pataschnick, Albany, NY). One impactor was positioned to sample incoming air at the eastern entrance of the tunnel; the second at the western exit of the tunnel.

CO_2 concentrations were measured at the tunnel exhaust chimney using a LiCor 7500 (Lincoln, NE) infrared hygrometer. This instrument was calibrated

A sample of vehicles were counted and identified by type from a video camera at the exit of the westbound tunnel. From these data, we will determine the number of passenger vehicles, medium duty truck, and heavy duty truck miles during each of the sampling periods.

3.2 Tire Tread Sampling

We have recently extracted Crumb Rubber Material (CRM) samples to determine the concentration of these markers in tires currently used in the US. Three CRM samples were represented by mixture of old recycled tires (both mixtures of different manufacturers), and the new defective Firestone tires (from the Ford Motor Company demonstration study). These samples were collected from projects that were completed in the State of Arizona. All three samples were sieved to select particles less than 150 μm.

Each tire wear sample was spiked prior to extraction with known amount of mixture of perdeuterated standard mixture. Tire wear samples were extracted twice with isopropanol, followed by three successive extractions with dichloromethane. Extracts were combined and filtrated through a pre-cleaned glass wool. Extracts were purified using column chromatography according to the procedure used by Kumata et al., 1996.

3.3 Organic Chemical Analysis

Aerosol samples were stored in precleaned glass jars at -20° C until analyzed. Four size-segregated aerosol samples will be analyzed for the tunnel inflow and outflow for the experiments done with the PCC and AR-ACFC pavement surfaces. Samples will be extracted using multiple sequential extractions in isopropanol and dichloromethane that has been shown to remove efficiently non-polar and polar compounds from the ChemVol substrates. Organic compounds will be identified by comparison with reference standards and mass spectral libraries. We have also assembled an extensive library of reference standard materials, including the tire wear marker compounds 24MoBt and NCBA.

The concentrations of 24MoBT and NCBA were measured by using Varian Saturn 4D GC/MS equipped with an ion-trap mass detector. Using this sampling and analysis procedure, a sample collected over 2-4 h will contain sufficient material for quantitative analysis of organic tracer compounds with concentrations of ~0.2 ng/m^3.

4 Results and Discussion

4.1 Tunnel Traffic

Traffic data was video-recorded on the I-10 east bound on may 27th and 28th 2004 and corresponded with the sampling periods presented in Table 1.The total time recorded was 10 hours. On may 27th, 4 hours of traffic were recorded from 10:00am-2:00pm and on may 28th, a total of 6 hours were recorded, from 7:00am-9:00am and from 10:00am-2:00pm.

The total of vehicles grouped by different classification categories are being obtained by manual counting using the tapes. The FHWA vehicle classification is being used (see Figure 2). For simplicity, and for the purpose of this experiment, vehicle types 5, 6, 7 are counted together as group 5; vehicle types 8, 9 10 are counted together as group 6, and vehicles 11, 12 13 are counted as group 7.

Analysis of the data was conducted using the ten hours recorded on May 27th and May 28th. The first stage was based on the counting every five minutes for a period of three hours (three one hour interval). According to the data obtained, the traffic was fairly constant during each hour. Based of these results, the counting for the remaining intervals was performed at 5 minutes intervals for every 15 minutes period. The table below summarized the ten hours period counting.

Table 2. Vehicle Counts

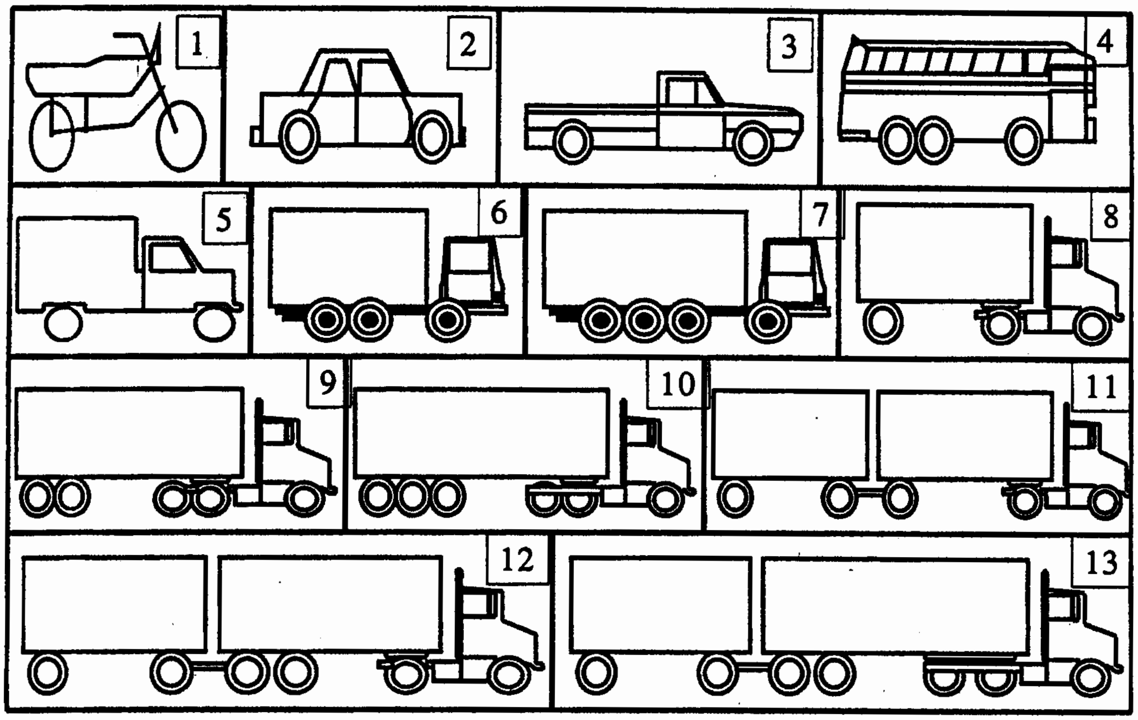
TOTAL NUMBERS OF VEHICLES

		VEHICLE TYPE							
DATE	**TIME**	**1**	**2**	**3**	**4**	**5***	**6***	**7***	**totals**
5/27/2004	10:00-11:00 AM	9	4417	1352	15	264	248	53	6359
5/27/2004	11:00-12:00 AM	13	4361	1320	13	291	231	0	6229
5/27/2004	12:00-1:00 PM	25	4673	1683	13	330	210	0	6934
5/27/2004	1:00-2:00 PM	19	5168	1767	43	288	204	0	7489
5/28/2004	7:00-8:00 AM	26	4431	1416	22	198	205	19	6317
5/28/2004	8:00-9:00 AM	33	5235	1469	32	194	172	9	7126
5/28/2004	10:00-11:00 AM	31	4736	1557	16	315	270	3	6928
5/28/2004	11:00-12:00 AM	40	4937	1617	7	291	201	0	7093
5/28/2004	12:00-1:00 PM	22	5429	1746	19	249	153	0	7618
5/28/2004	1:00-2:00 PM	16	5546	1767	22	249	183	0	7783
	TOTAL VEHICLES	**235**	**48935**	**15697**	**206**	**2669**	**2077**	**84**	**69903**

* VEHICLE TYPE 5 CORRESPONDS TO TYPE 5, 6, 7 FROM FHWA
* VEHICLE TYPE 6 CORRESPONDS TO TYPE 8,9,10 FROM FHWA
* VEHICLE TYPE 7 CORRESPONDS TO TYPE 11,12,13 FROM FHWA

4.2 Aerosol Concentrations

Efforts and results in this task will be reported on in the next period.



1. Motorcycles
2. Passenger Cars
3. Two Axles. Four Tires Single units
4. Buses
5. Two Axles. Six tires Single Unit
6. Three Axle Single Units
7. Four or More Axle Single Units
8. Four or Less Axle Single Trailers
9. Five Axle Single Trailers
10. Six or More Axle Single Trailers
11. Five or Less Axle Multi-Trailers
12. Six Axle Multi-Trailers
13. Seven or More Axle Multi-Trailers

Figure 2. FHWA Vehicle Class Illustration and Definitions.

4.3 Tire Marker Compounds

24MoBT concentrations found in CRM samples purified using column chromatography agree with the data obtained by Kumata et al., 1997 and Reddy and Quinn, 1997. Kumata et al. found a mean concentration of 2.3 ppm in particles generated mechanically of tire tread rubber from four different tires (Kumata et al., 1997). The concentration of 24MoBT in crumb rubber material was 3.8 ppm (Reddy and Quinn, 1997).

Table 3: 24MoBT concentrations found in crumb rubber samples purified using column chromatograpy.

Sample	ng mg^{-1}	Sample Description
CRM # 1	2.45	Used tires, mixture of different brands
CRM # 2	1.49	Used tires, mixture of different brands
CRM # 3	3.12	New Firestone tires (Ford Study)
Average	**2.35**	

24MoBT and NCBA were identified in the samples of fine particulate matter collected in the Caldecott tunnel (California) in 1997 (Allen et al., 2001; Alexandrova and Allen, 2004). The emission rates of 24MoBT and NCBA per mass of carbon in fuel burned were calculated; this is a precise and directly measured emission rate, that can be scaled to an estimate of tire wear mass emission rates. Emission rates of 24MoBT (5.10 μg/kg of C in fuel burned) and NCBA (1.11 μg/kgC) from the LDV fleet were higher than from the HDV fleet (2.90 and 0.80 μg/kgC). Higher benzothiazolamine emission rates for the LDV fleet relative to the HDV fleet is likely due to the different composition of automobile and truck tires (Kim et al., 1990).

The total amount of tire wear material can be calculated by multiplying the emission rate of tire wear markers 24MoBT and NCBA by the inverse fraction of these markers in whole tire treads. Using the values above, the calculated tire wear emission rate is greater than the *total* measured aerosol emission rate. We believe that the methods used by Kumata et al. and Reddy and Quinn, which were designed to measure the amount of tire wear markers which leach into water, underestimate by an order of magnitude the amount of 24MoBT and NCBA in tire tread. For this task we will collect a representative sample of tread from used tires in Arizona, then extract them using a method comparable to the aggressive solvent extractions used for aerosol samples.

4.4 Tire Wear Emission Rate

Using the measured concentrations of tire wear markers, tire wear emission rates per kg of carbon burned in the fuel were determined as

$$E_i = (C_{i1} - C_{i0}) / (C_{c1} - C_{c0})$$

where E_i is the emission rate for species i; C_{i0} and C_{i1} are the concentrations of species i at the inlet and outlet, respectively. C_{c0} and C_{c1} are the concentrations of carbon at the inlet and outlet, respectively. We have successfully used this method to determine emission rates in the Caldecott tunnel (Allen et al., 2001). Since more than 95% of carbon in fuel is converted to CO_2, concentrations of CO_2 are good approximations of C_{c0} and C_{c1}.

Emission rates, E_i, are based on the amount of fuel burned are stable and very useful for tailpipe emissions, but one expects tire wear emissions to scale with the distance driven. The relative emissions of tire wear for the different paving surfaces will be determined by the change in E_i between the experiments assuming a constant average fuel economy before and after paving.

4.5 Roadway Characteristics

The roughness and frictional characteristics of a pavement surface play an important role in road safety and tire wear. Factors such as tire geometry, traveling speed of the vehicle, the minuscule surface structure between the interfacing contact areas (texture), and contamination of the pavement surface play an important role on the frictional characteristics of the pavement.

To better understand the interaction of the tire and pavement surface in this experiment, roughness measurements (IRI), and frictional characteristics (macro-texture) were measured by ADOT. An example of the friction data before and after the overlay is shown in Figure 3.

Roughness measurement

One important characteristic that gives an indication of the pavement functional condition is the roughness.

Pavement roughness is the distortion of the road surface that contribute to an undesirable, unsafe, uneconomical or uncomfortable ride.

ADOT utilizes a profilometer to measure the International Roughness Index(IRI) that is the ratio of the accumulated suspension motion to the distance traveled expressed in units of inches per mile. The index summarizes the longitudinal surface profile in a wheelpath.

The IRI provides a numeric scale of measuring roughness; this scale range from 0 to 1267 in/mi with larger values indicating greater roughness. The approximate break point between what is considered rough and smooth pavement is often considered to be 125 in/mi. The specific FHWA guidelines that relates IRI levels to condition is presented in table 4.

Condition categories	**IRI rating (in/mi)**	
	Interstate	Other
Very good	<60	<60
Good	60-94	60-94
Fair	95-119	95-170
Mediocre	120-170	171-220
Poor	>170	>220

Table 4. Relation between IRI and condition (FHWA 1999)

ADOT performed the IRI measurement of the east and west lanes of the tunnel section, before and after the overlay with asphalt rubber . Five lanes in each direction east and west were measured; lanes 1-4 plus the HOV lane. The plots to compare the surface profiles are included in appendix A.

The table below summaries the IRI measurements before and after the overlay.

SECTION	**IRI (in/mi)**	
	PCCP	AR-ACFC
I010EHOV	96.34	43.57
I010ELN1	123.2	59.03
I010ELN2	104.29	48.81
I010ELN3	111.87	47.8
I010ELN4	115.3	52.91
I010WHOV	85.44	32.51
I010WLN1	87.94	37.79
I010WLN2	85.4	46.92
I010WLN3	96.83	46.11
I010WLN4	97.75	36.81

Table 5. IRI before and after overlay in tunnel section

According to this table, an improvement in the IRI was obtained after the overlay with values below 60 in/mi.

Friction measurement

Another important characteristic in assessing a pavement functional characteristics is the surface friction.

Pavement surface friction is the force developed at the tire-interface that resists sliding when braking forces are applied to the vehicle tires.

ADOT utilizes a MU meter or Side Force testing device. Side force testers are designed to simulate a vehicle's ability to maintain control in curves. They function by maintaining a test wheel in a plane at an angle to the direction of motion, while the wheel is allowed to roll freely. The developed side force is then measured perpendicular to the plane of rotation.

Measurements are reported as a skid number, that is, the measured value of friction times 100.

For Arizona, the intervention level for friction reported for interstate, primary and secondary roadways is 34(MuMeter).

ADOT performed the surface friction measurement of the east and west lanes of the tunnel section, before and after the overlay with asphalt rubber . Similar to the roughness measurement, five lanes in each direction east and west were tested; lanes 1-4 plus the HOV lane. The plots to compare the surface friction values for each lane before and after the overlay are included in appendix B.

The table below shows a summary of the values obtained.

SECTION	AVERAGE FRICTION VALUE(MU)	
	PCCP	AC
I010EHOV	0.54	0.66
I010ELN1	0.6	0.61
I010ELN2	0.49	0.61
I010ELN3	0.47	0.6
I010ELN4	0.47	0.54
I010WHOV	0.51	0.58
I010WLN1	0.64	0.57 *
I010WLN2	0.5	0.59
I010WLN3	0.44	0.59
I010WLN4	0.42	0.58

Note:
* Average value lower after overlay

Table 6. Friction test deck park tunnel summary

Pavement temperature

Temperature thermistors (COMMAND Center Button Sensors) were also installed to monitor the pavement surface temperatures. Sensors outside the tunnel were damaged by the compaction process during the overlay of the AR-ACFC. Sensors inside the tunnel were functioning but the access to retrieve the data was a challenge since there are no parking shoulders inside the tunnel.

Data of pavement surface temperature was collected for the east and westbound. For the eastbound one sensor collected temperature data every 20 minutes from October 17th to November 14th 2004.For the westbound two sensors were located, and pavement surface temperature were collected from October 24th to November 21st 2004.

The graph below shows the pavement temperature profile for east and westbound for the period of time when both measurements were taken (October 24th to November 14th). For the westbound the average of the two sensors measurements was used.

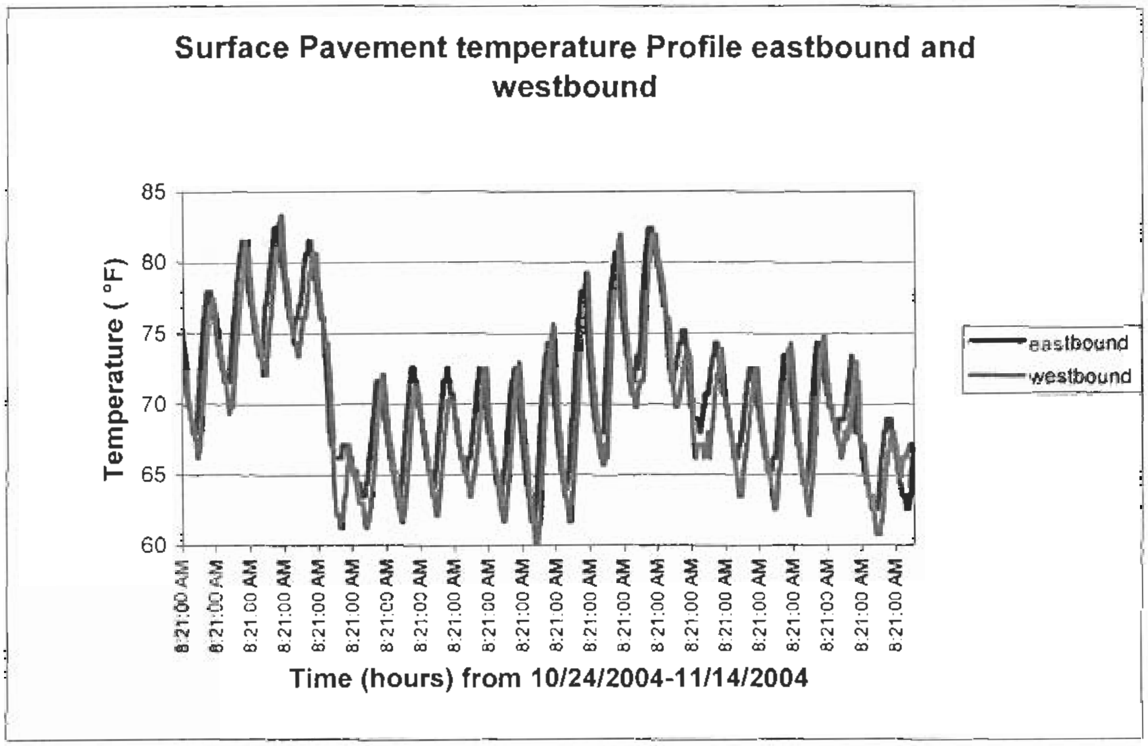


Table 7. Surface Pavement Temperature Profile.

5 Conclusions

Conclusions will be drawn as more data analysis and progress are completed.

As mentioned in the introduction, it is envisioned that the final product of this study will provide ADOT with tire wear emission data for use in the federally-mandated air quality modeling for the Phoenix airshed.

6 Acknowledgements

Thanks are due to Arnold Burnham, ADOT's Project Manager on this research, Arnold Burnham, Kathleen Sommer and Mark Wheaton, who were the contact and organizer of the project schedule, James Delton, Assistant State Engineer, Dennis Rusher and Ernie Johnson, Pavement Management Division; Edward Walsh and John Kruger of the ADOT tunnel maintenance department were extremely helpful in providing logistical support including access to the tunnel, electric power, and a bucket truck. We could not have done this experiment without their kind assistance.

7 References

Allen J. O., Dookeran N. M., Taghizadeh K., Lafleur A. L., Smith K. A., and Sarofim A. F., 1996: Measurement of polycyclic aromatic hydrocarbons associated with size-segregated atmospheric aerosols in Massachusetts, *Environ. Sci. Technol.*, 30:1023-1031.

Allen J. O., Mayo P. R., Hughes L. S., Salmon L. G., Cass G. R.. Emissions of size-segregated aerosols from on-road vehicles in the Caldecott Tunnel, *Environ. Sci. Technol.*, 35:4189-4197, 2001.

U. S. Environmental Protection Agency, *MOBILE 6.1 Particulate Emission Factor Model Technical Description*, EPA420-R-03-001, 2003.

Gertler A. W., Sagebiel J. C., Wittorff D. N., Pierson W. R., Dippel W. A., Freeman D., Sheetz L., 1997: Vehicle Emissions in Five Urban Tunnels, Final Report to Coordinating Research Council, Project E-5.

Hildemann L.M., Mazurek, M.A., Cass G.R., Simoneit B.R.T., 1991: Quantitative characterization of urban sources of organic aerosol by high-resolution gas chromatography. *Environ. Sci. Technol.*, 25:1311-1325.

Kumata H., Takada H., Ogura N., 1996: Determination of 2-(4-morpholinyl)benzothiazole in environmental samples by a gas chromatograph equipped with a flame photometric detector, *Anal. Chem.*, 68:1976-1981.

Kumata H., Sanada Y., Takada H., and Ueno T., 2000: Historical trends of N-cyclohexyl-2-benzothiazolamine, 2-(4-morpholinyl)benzothiazole, and other anthropogenic contaminants in the urban reservoir sediment core, *Environ. Sci. Technol.*, 34:246-253.

Kumata H., Yamada J., Masuda K., Takada H., Sato Y., Sakurai T., and Fujiwara K., 2002: Benzothiazolamines as tire-derived molecular markers: Sorptive behavior in street runoff and application to source apportioning, *Environ. Sci. Technol.*, 36:702-708.

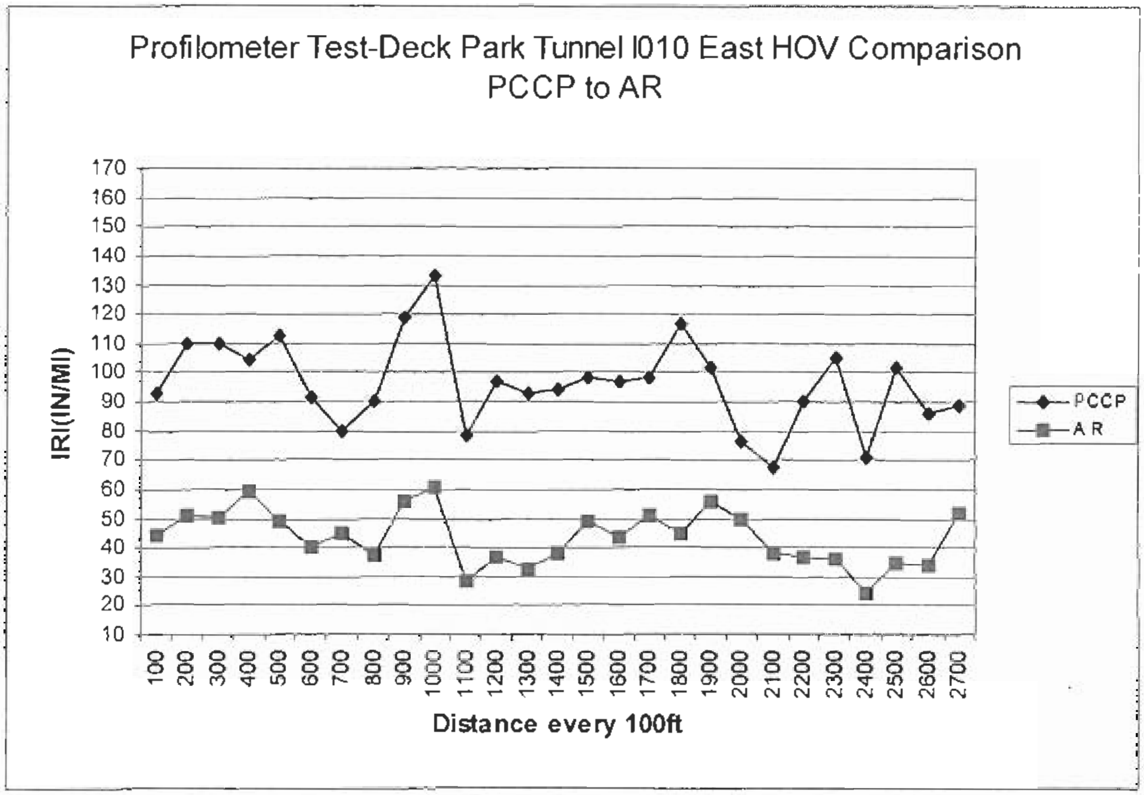
Reddy C. M., Quinn J. G., 1997: Environmental Chemistry of Benzothiozols Derived from Rubber, *Environ. Sci. Technol.*, 31:2847-2853.

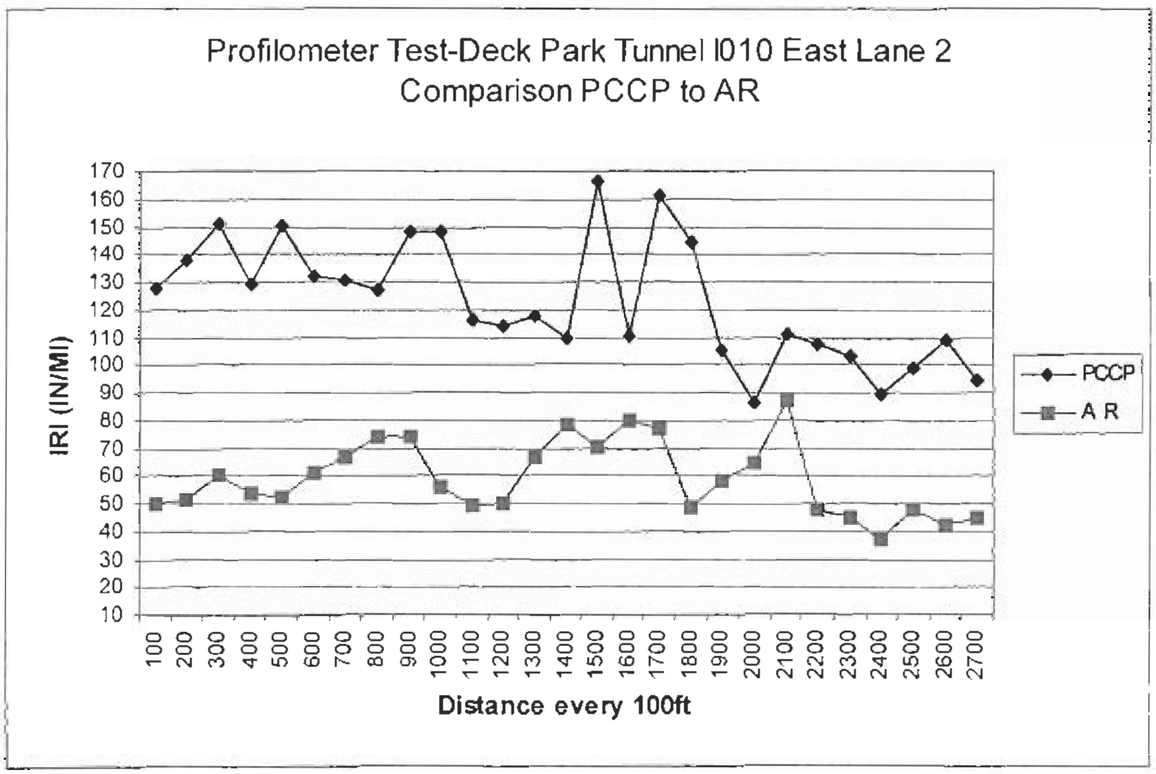
Rogge, W.F., Hildemann L.M., Mazurek, M. A., Cass, G. R., Simoneit, B. R. T., 1993: Sources of fine organic aerosol: 2. Noncatalyst and catalyst-equipped automobiles and heavy-duty diesel trucks, *Environ. Sci. Technol.*, 27:636-651.

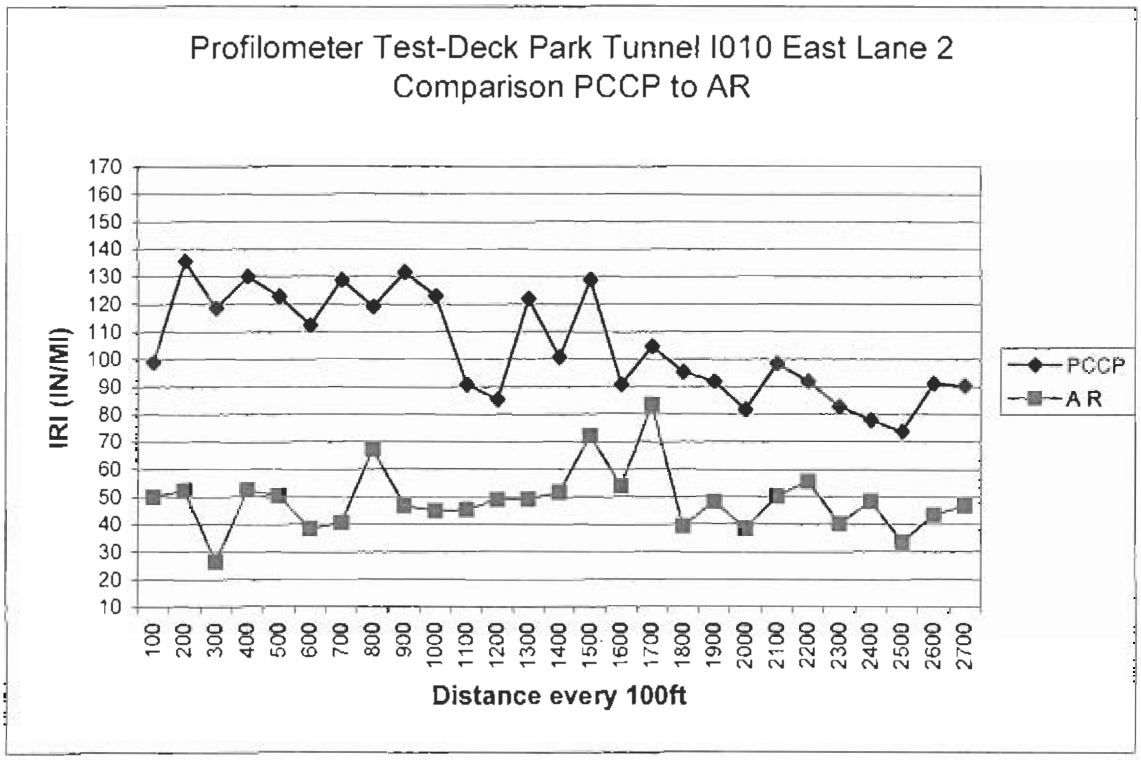
Schauer, J.J., Rogge, W. F., Hildemann, L.M., Mazurek, M. A., Cass, G. R., Simoneit, B. R. T., 1996: Source apportionmnt of airborn particulate matter using organic compounds as tracers. *Atmos. Environ.*, 30, 3837-3855.

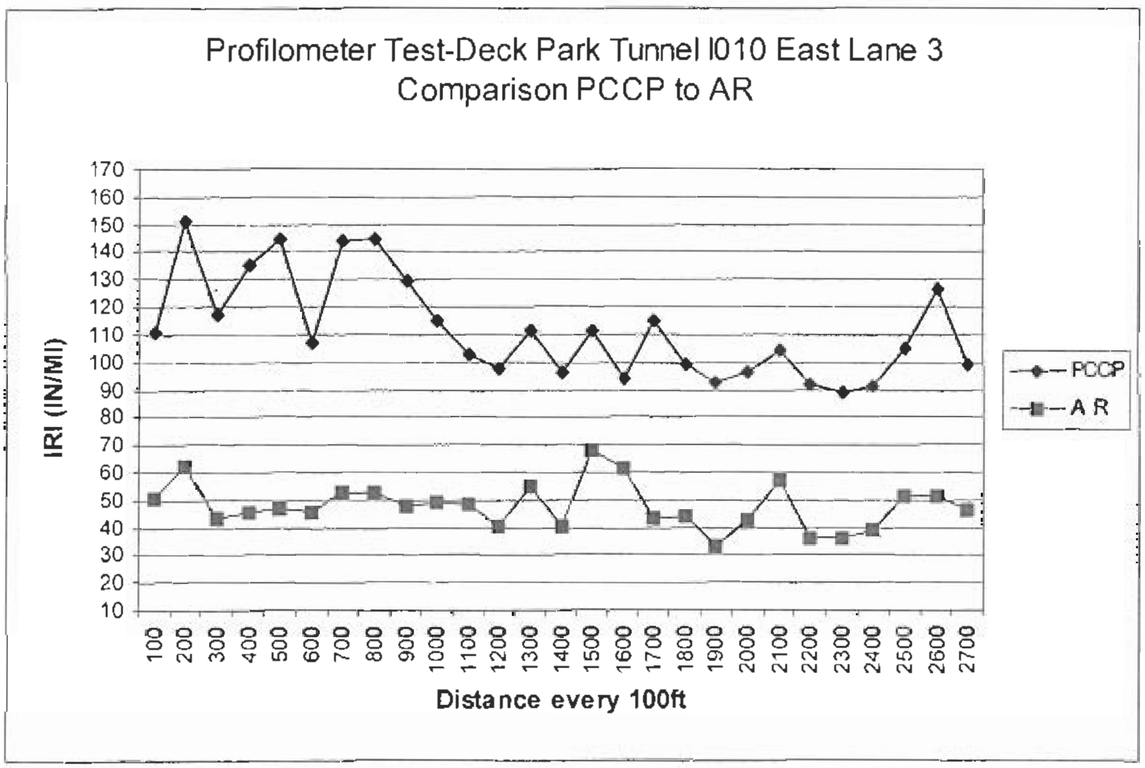
Schauer J.J., Kleeman M.J., Glen G.R., and Simoneit B.R.T., 1999: Measurement of emissions from air pollution sources. 2. C1 through C30 organic compounds from medium duty diesel trucks, *Environ. Sci. Technol.*, 33:1578-1587.

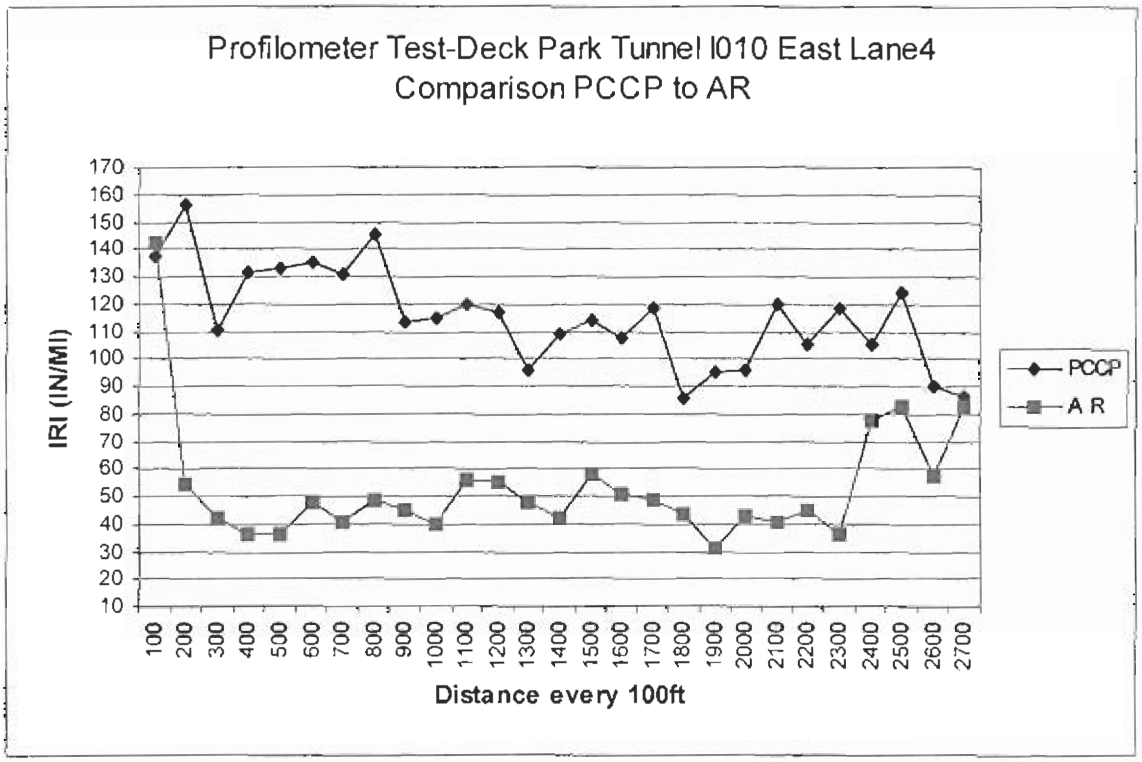
APPENDIX A:
IRI TEST RESULTS

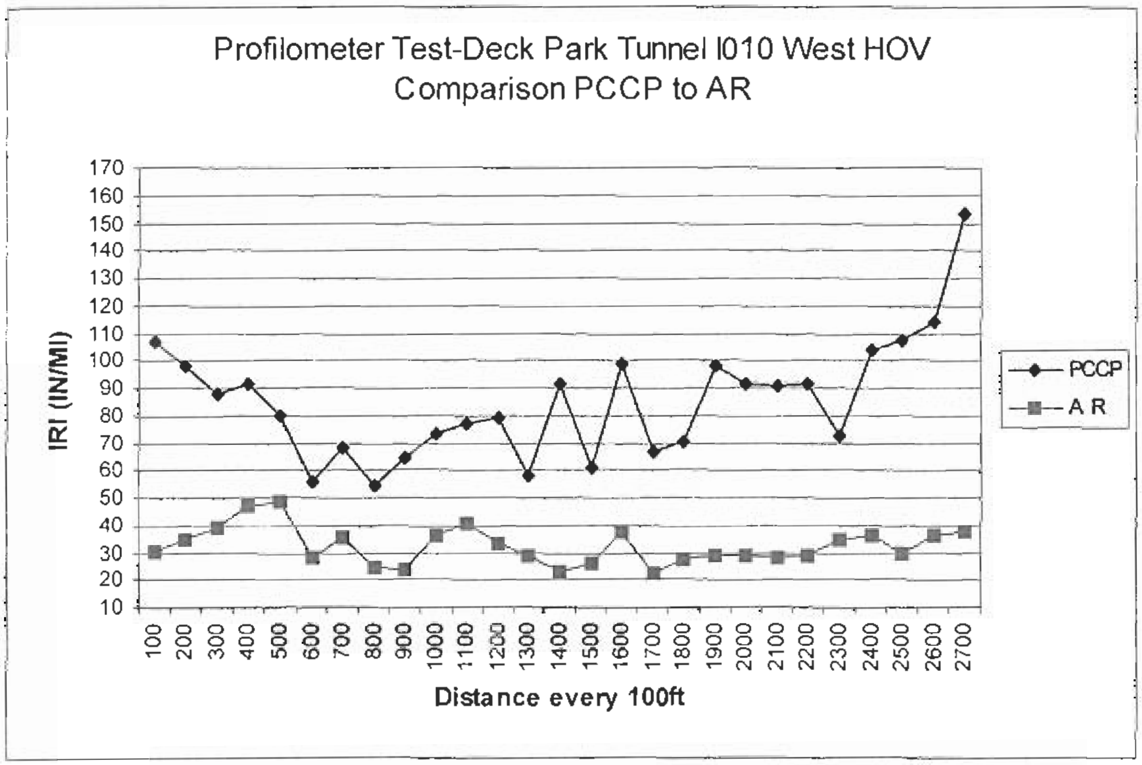

Profilometer Test-Deck Park Tunnel I010 East HOV Comparison
PCCP to AR
IRI(IN/MI)
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
Distance every 100ft
PCCP
A R

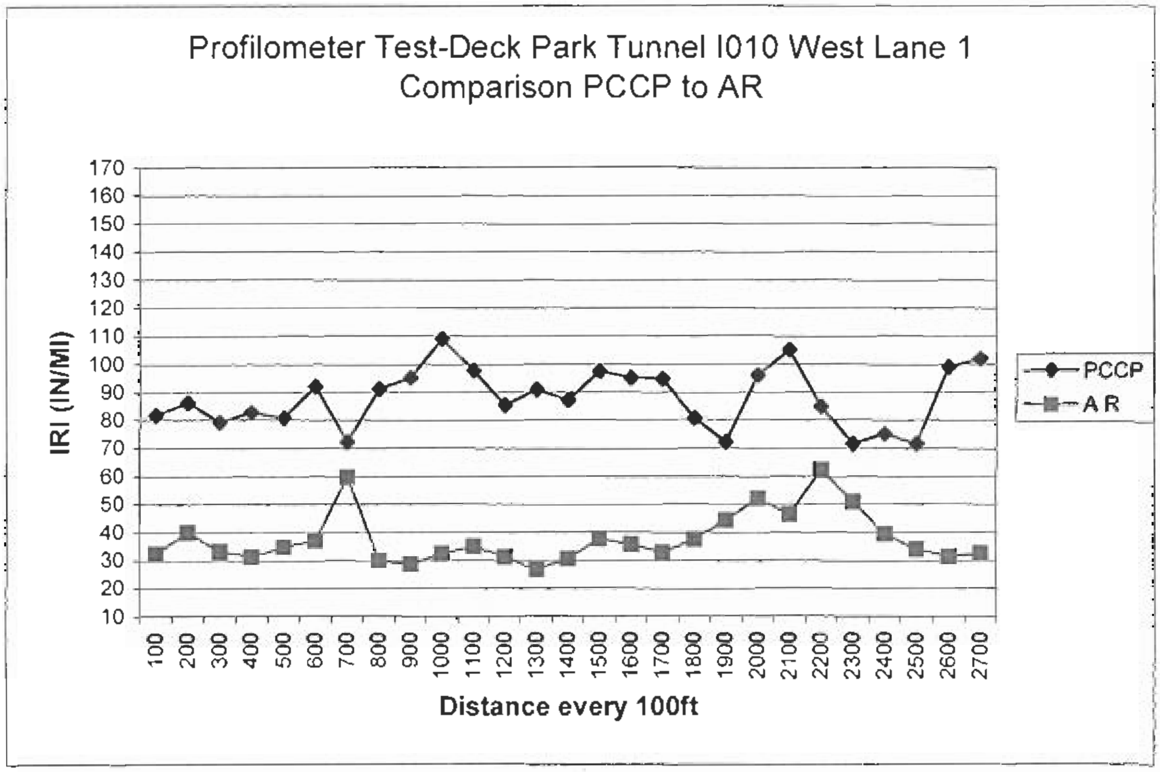

Profilometer Test-Deck Park Tunnel I010 East Lane 2
Comparison PCCP to AR
IRI (IN/MI)
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
Distance every 100ft
PCCP
A R

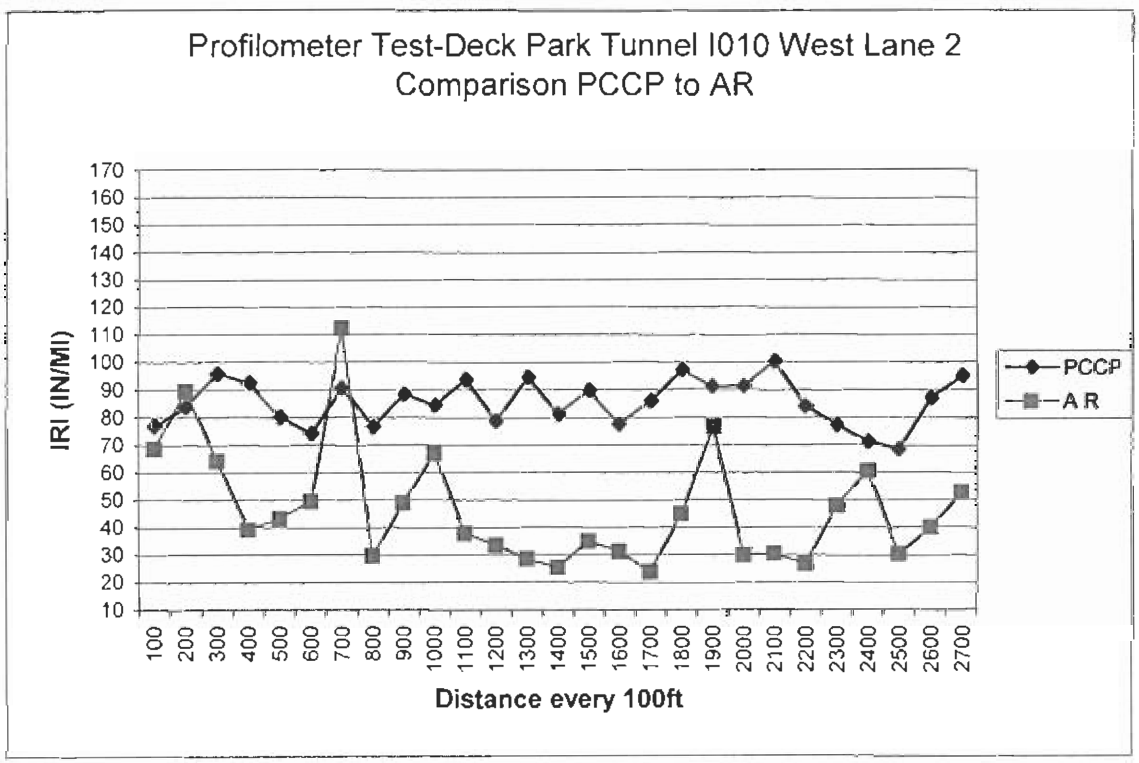

Profilometer Test-Deck Park Tunnel I010 East Lane 2
Comparison PCCP to AR
IRI (IN/MI)
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
Distance every 100ft
PCCP
A R

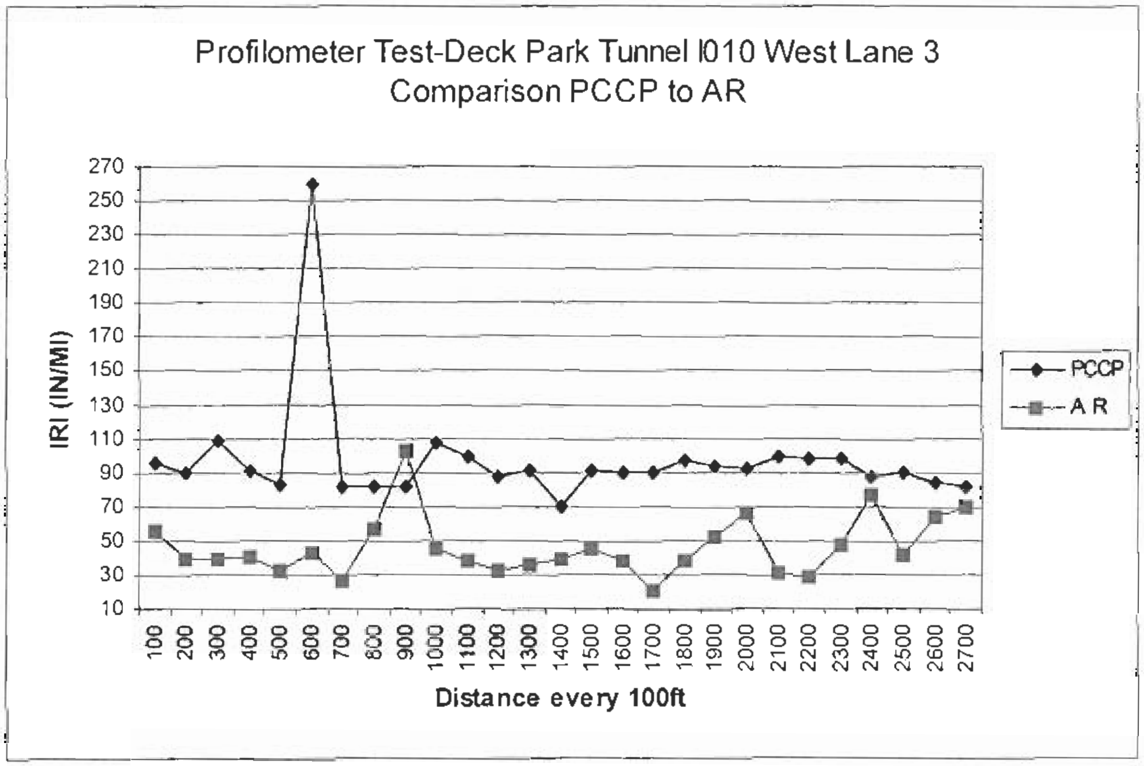

Profilometer Test-Deck Park Tunnel I010 East Lane 3
Comparison PCCP to AR
IRI (IN/MI)
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
Distance every 100ft
PCCP
A R

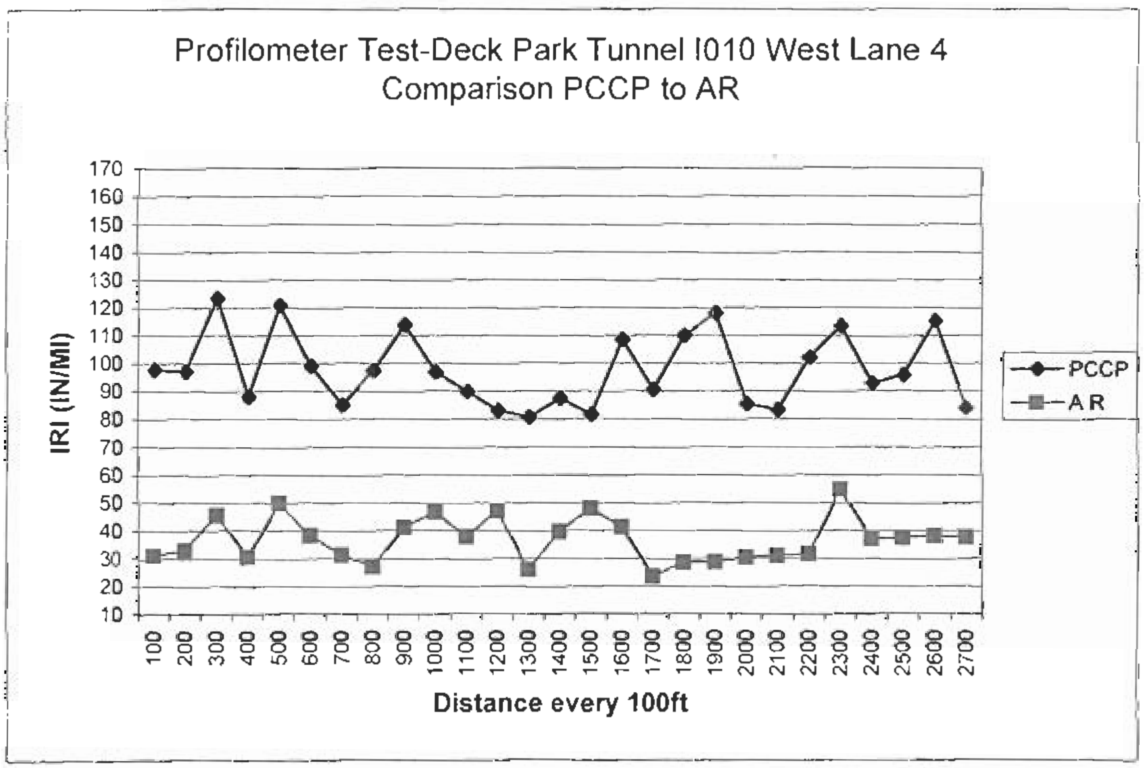

Profilometer Test-Deck Park Tunnel I010 East Lane4
Comparison PCCP to AR
IRI (IN/MI)
Distance every 100ft
PCCP
A R


Profilometer Test-Deck Park Tunnel I010 West HOV
Comparison PCCP to AR
IRI (IN/MI)
Distance every 100ft
PCCP
A R


Profilometer Test-Deck Park Tunnel I010 West Lane 1
Comparison PCCP to AR
IRI (IN/MI)
Distance every 100ft
PCCP
A R

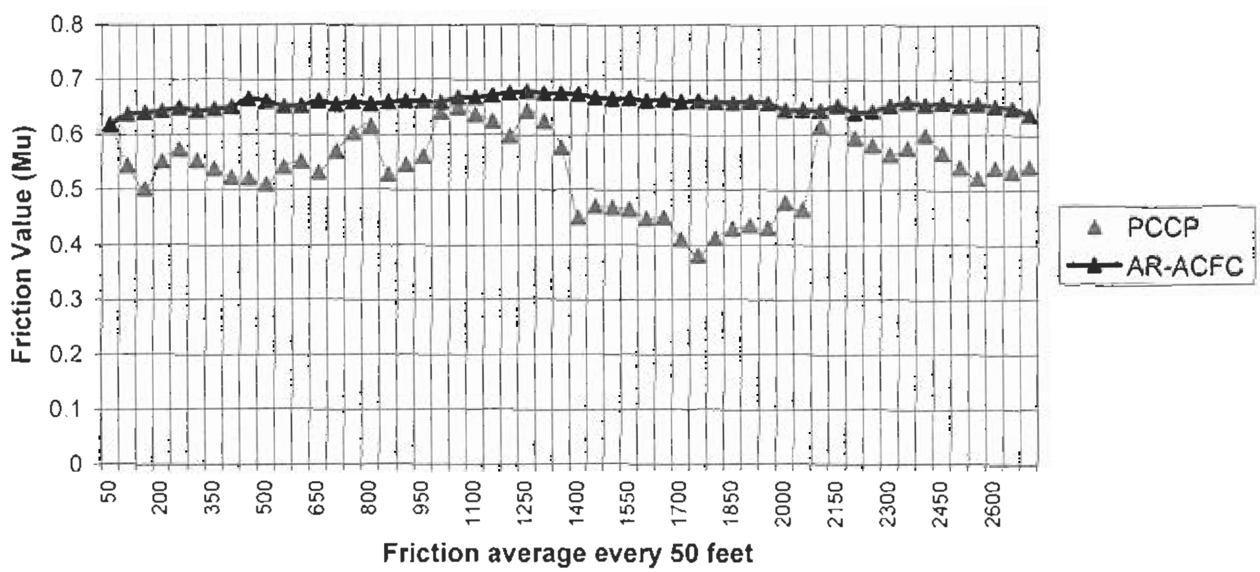

Profilometer Test-Deck Park Tunnel I010 West Lane 2
Comparison PCCP to AR
IRI (IN/MI)
Distance every 100ft
PCCP
A R


Profilometer Test-Deck Park Tunnel I010 West Lane 3
Comparison PCCP to AR
IRI (IN/MI)
Distance every 100ft
PCCP
AR

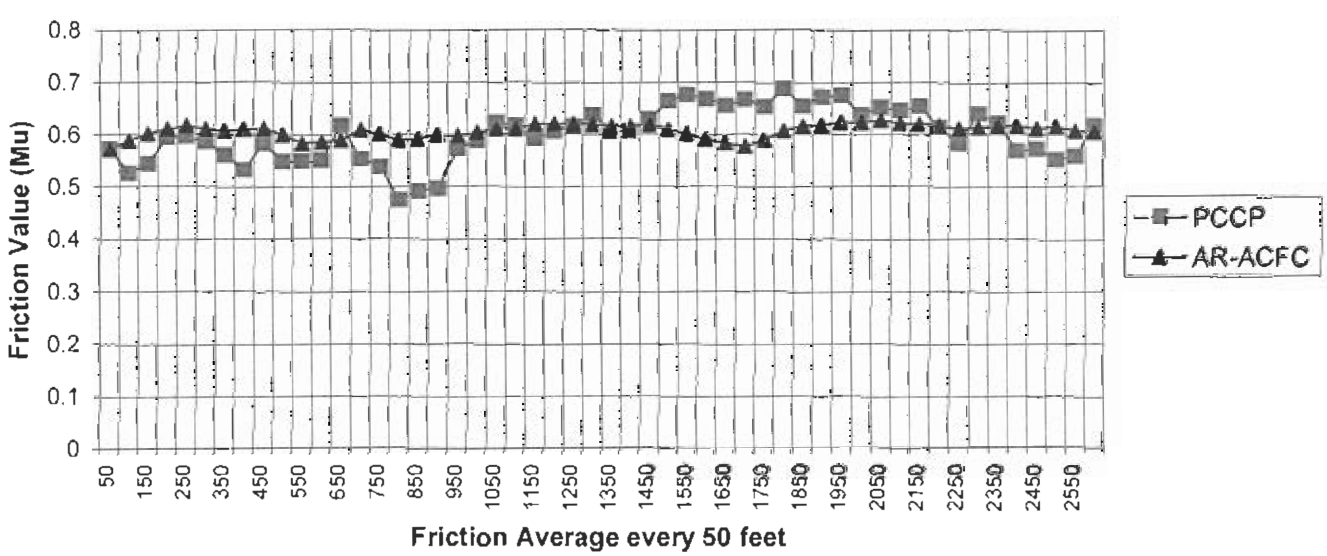

Profilometer Test-Deck Park Tunnel I010 West Lane 4
Comparison PCCP to AR
IRI (IN/MI)
Distance every 100ft
PCCP
AR

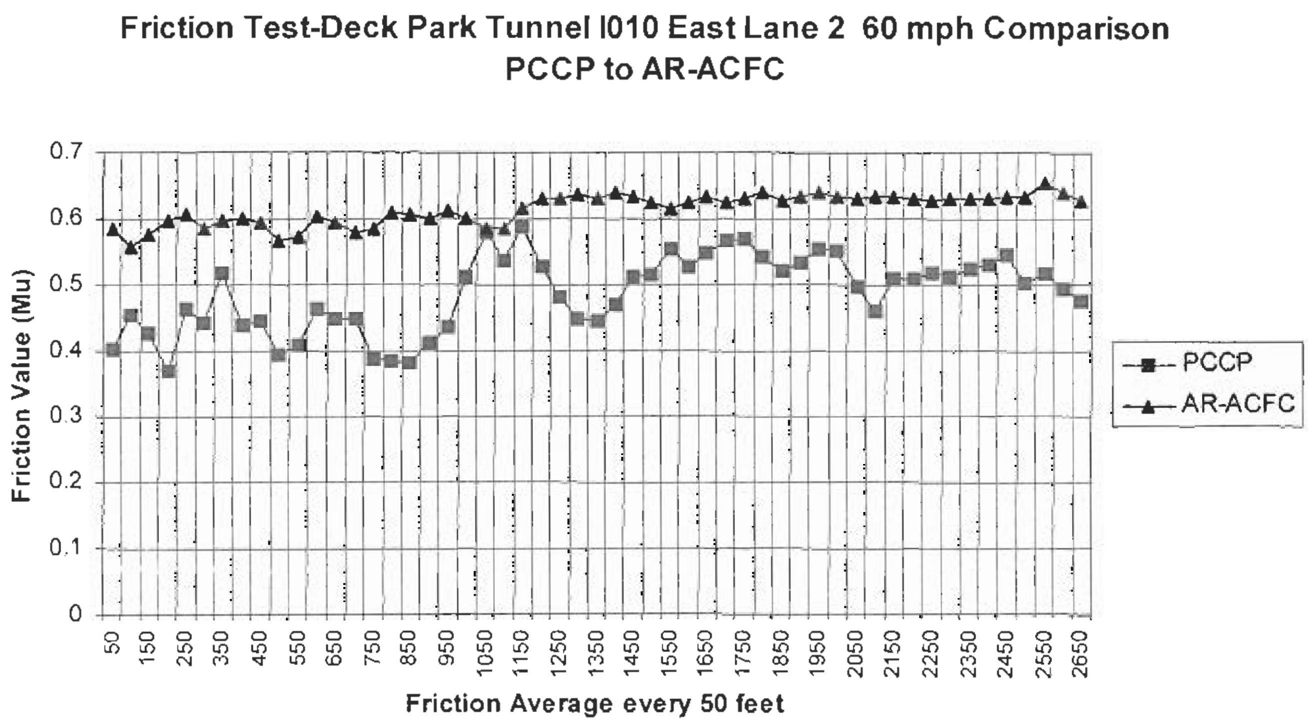
APENDIX B.
FRICTION TEST RESULTS

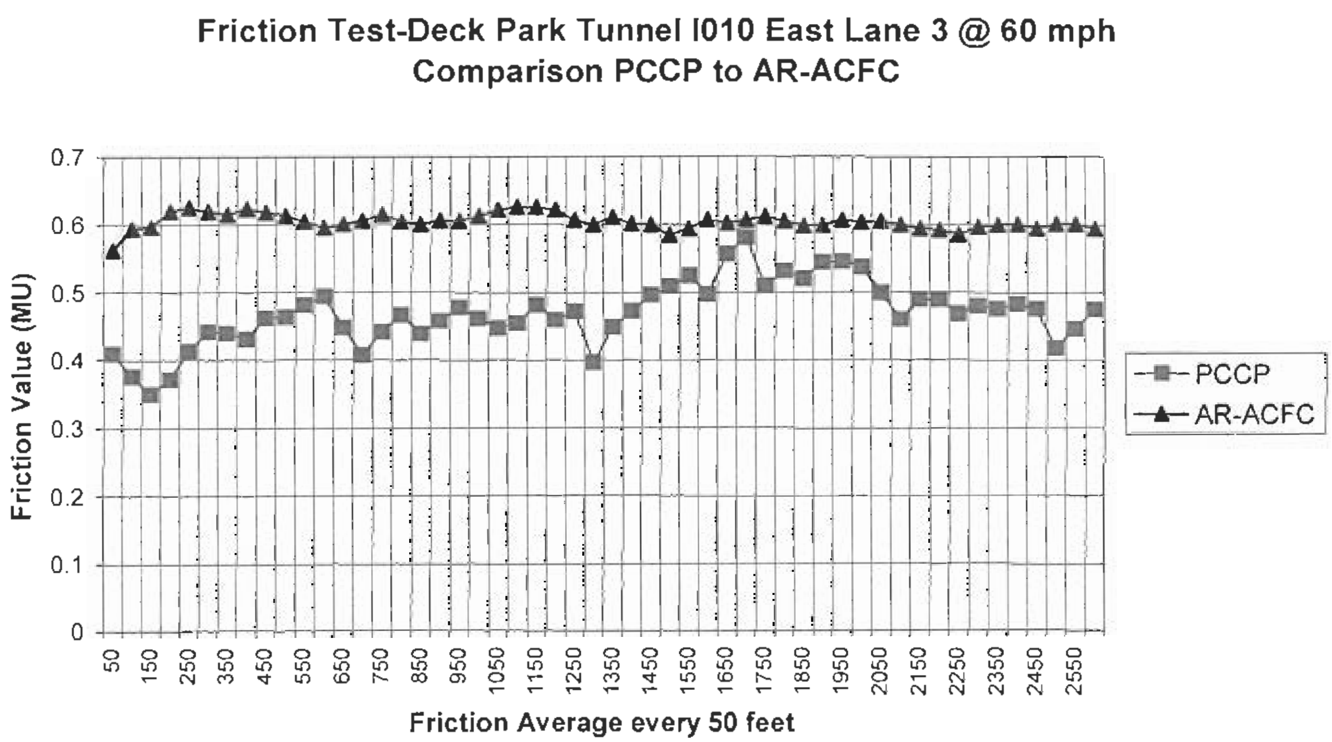
**Friction Test-Deck Park Tunnel I010 East HOV Lane @ 60 mph
Comparison PCCP to AR-ACFC**



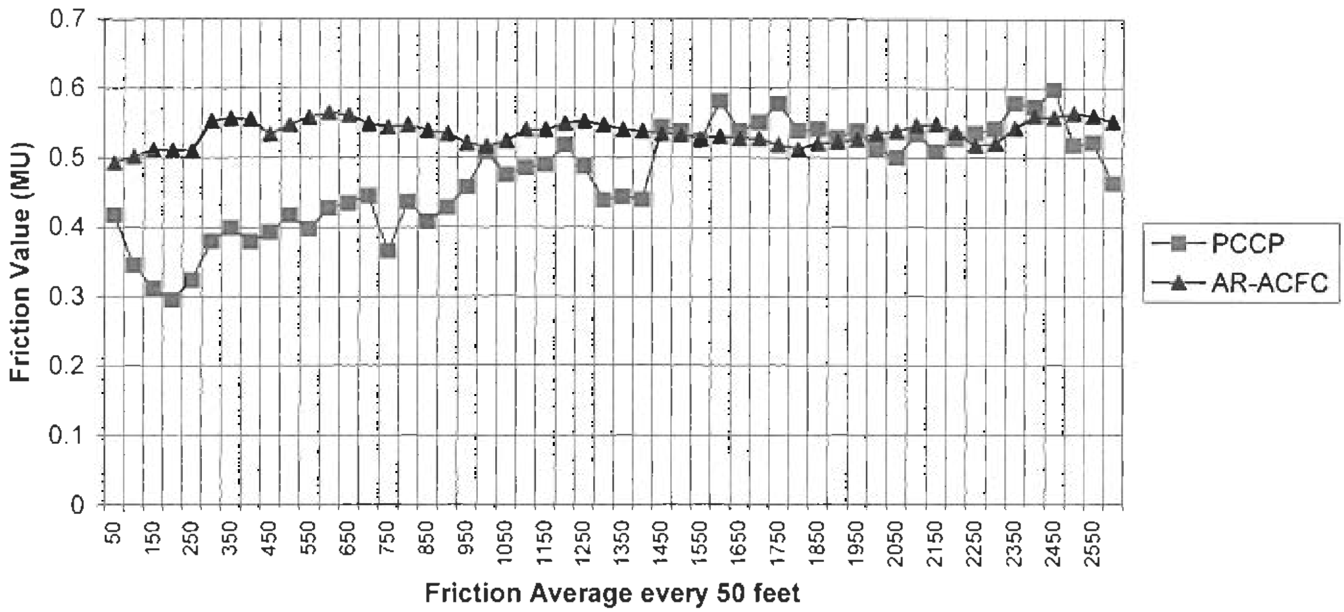
**Friction Test-Deck Park Tunnel I010 East Lane 1 @ 60 mph
Comparison PCCP to AR-ACFC**



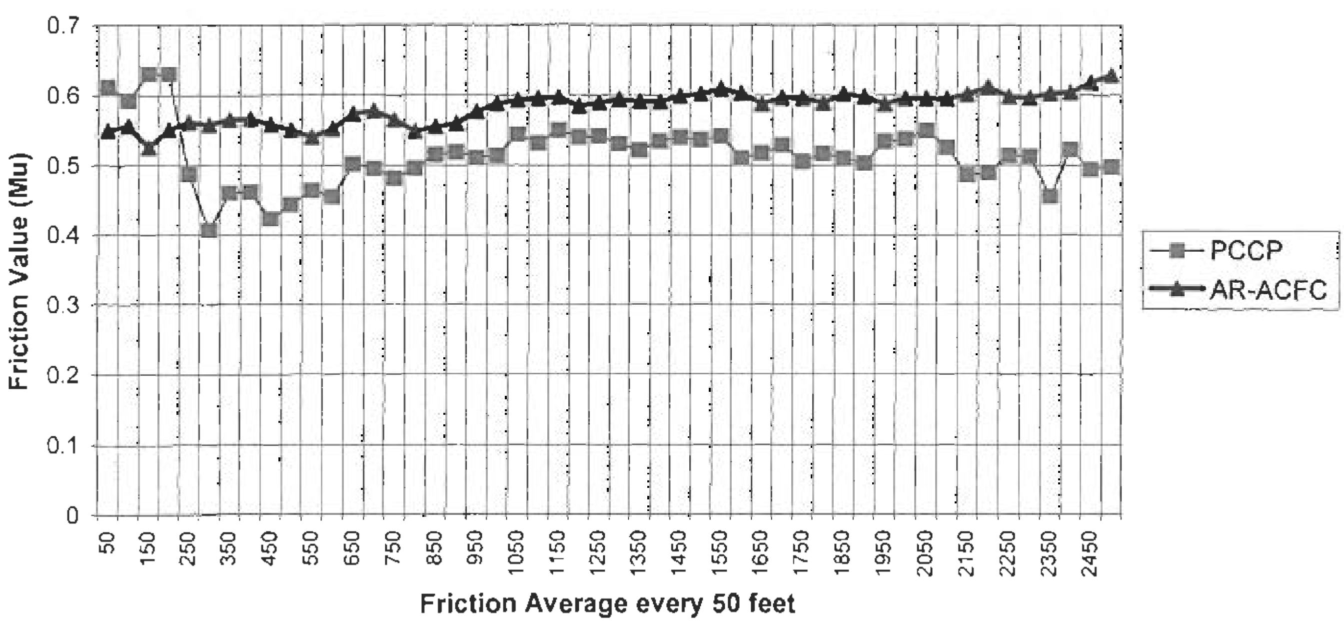

Friction Test-Deck Park Tunnel I010 East Lane 2 60 mph Comparison
PCCP to AR-ACFC
Friction Value (Mu)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
50
150
250
350
450
550
650
750
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2050
2150
2250
2350
2450
2550
2650
Friction Average every 50 feet
PCCP
AR-ACFC


Friction Test-Deck Park Tunnel I010 East Lane 3 @ 60 mph
Comparison PCCP to AR-ACFC
Friction Value (MU)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
50
150
250
350
450
550
650
750
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2050
2150
2250
2350
2450
2550
Friction Average every 50 feet
PCCP
AR-ACFC

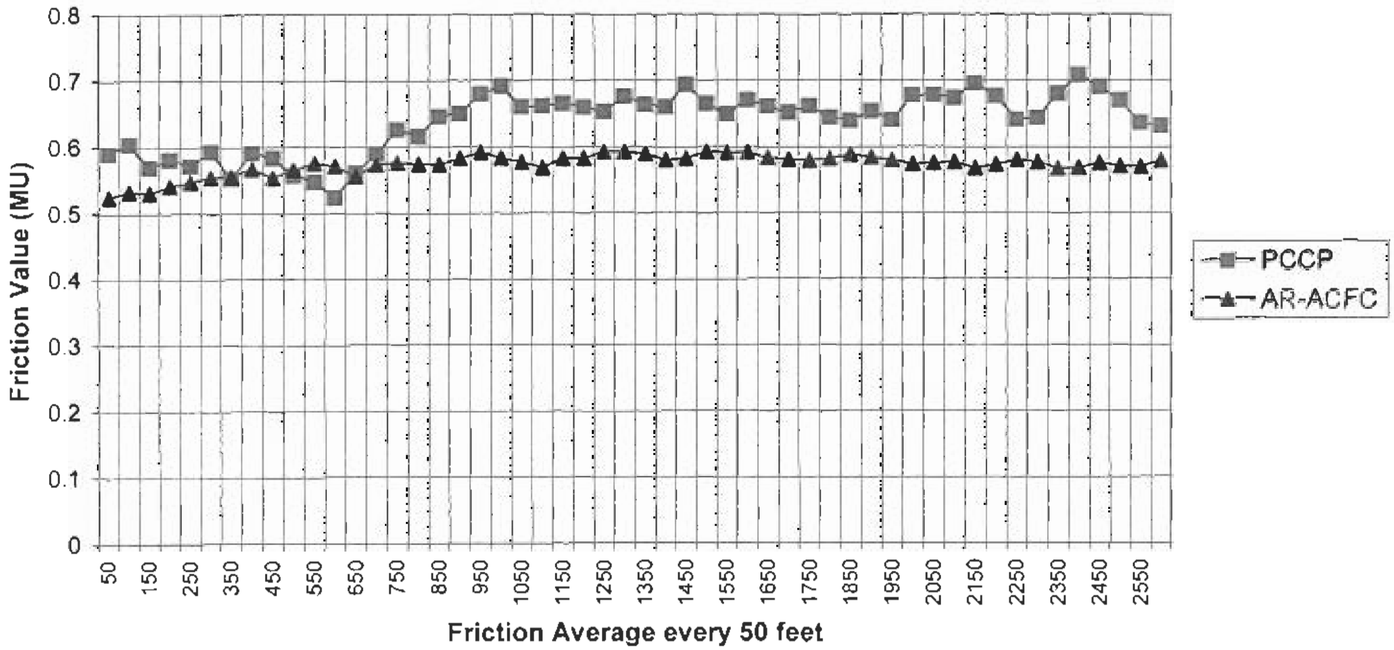
Friction Test-Deck Park Tunnel I010 East Lane 4 @ 60 mph
Comparison PCCP to AR-ACFC



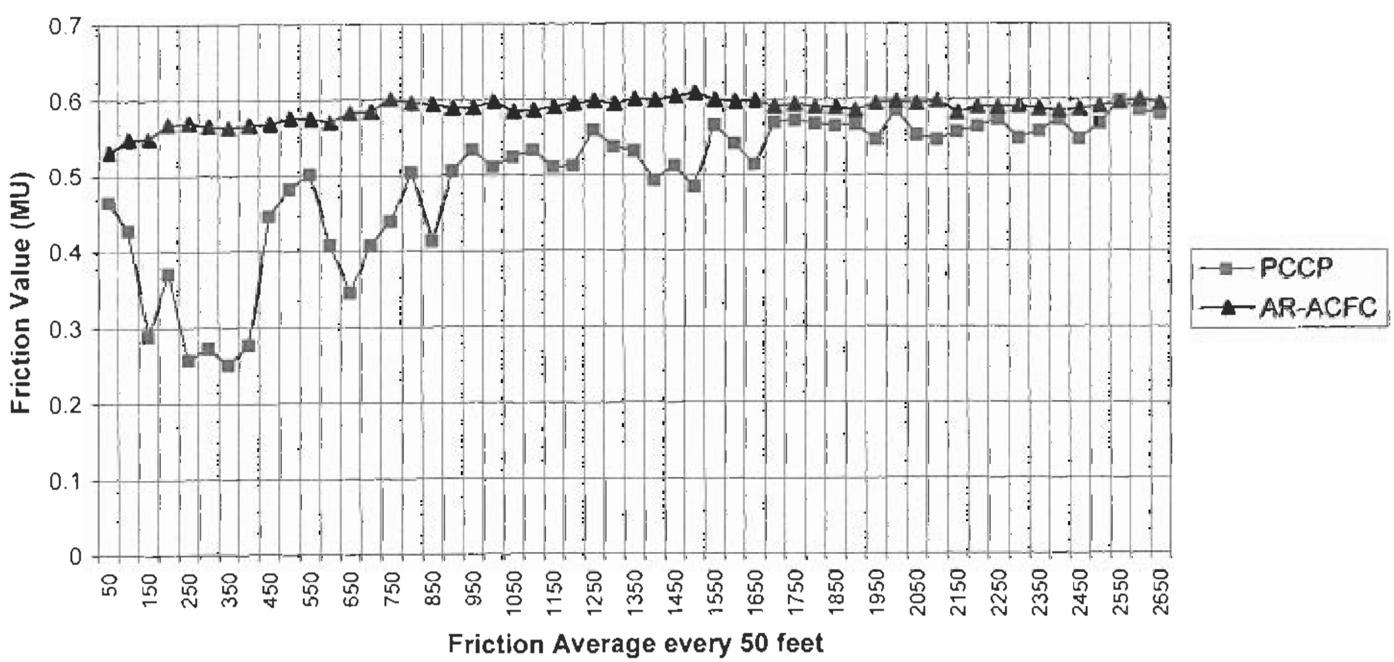
Friction Test-Deck Park Tunnel I010 West HOV Lane @ 60 mph
Comparison PCCP to AR-ACFC



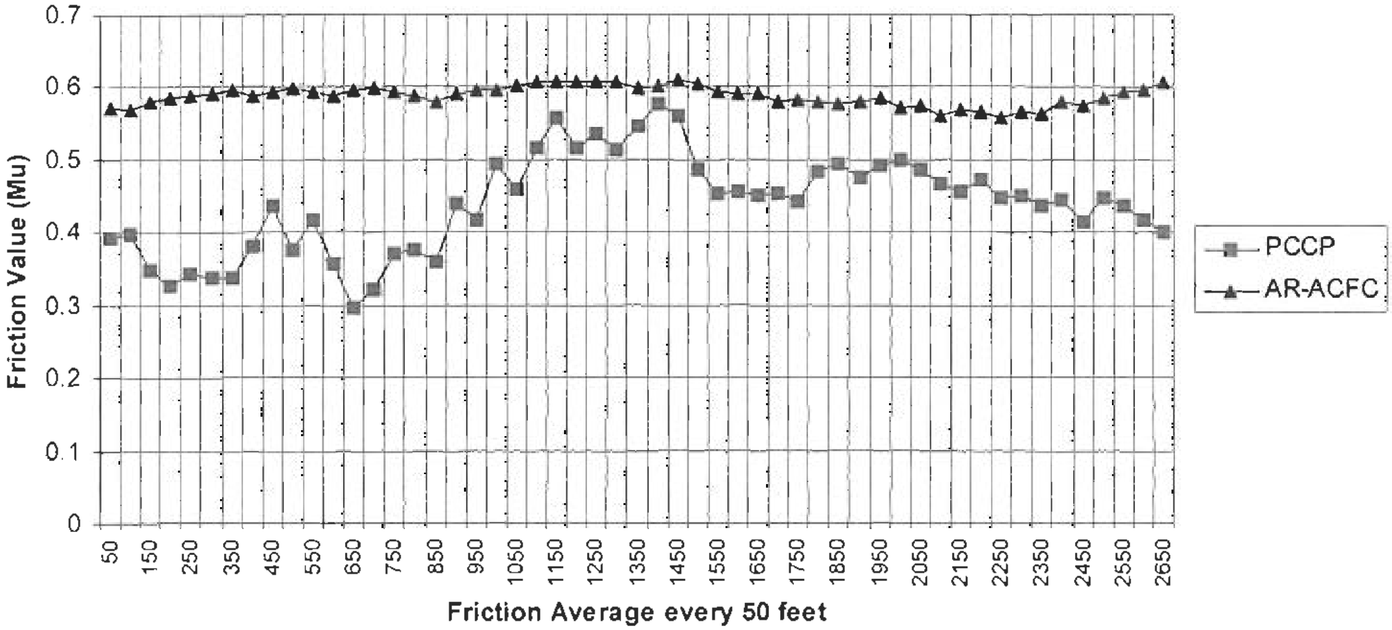
Friction Test-Deck Park Tunnel I010 West Lane 1 @ 60 mph Comparison PCCP to AR-ACFC



Friction Test-Deck Park Tunnel I010 West Lane 2 @ 60 mph Comparison PCCP to AR-ACFC



Friction Test-Deck Park Tunnel I010 West Lane 3 @ 60 mph Comparison PCCP to AR-ACFC



Friction Test-Deck Park Tunnel I010 West Lane 4 @ 60 mph Comparison PCCP to AR-ACFC